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Life cycle assessment of a waste lubricant oil management system

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Abstract

Purpose This paper compares 16 waste lubricant oil (WLO) systems (15 management alternatives and a system in use in Portugal) using a life cycle assessment (LCA). The alternatives tested use various mild processing techniques and recovery options: recycling during expanded clay production, recycling and electric energy production, re-refining, energy recovery during cement production, and energy recovery during expanded clay production.

Methods The proposed 15 alternatives and the actual present day situation were analyzed using LCA software UMBERTO 5.5, applied to eight environmental impact categories. The LCA included an expansion system to accommodate co-products.

Results The results show that mild processing with low liquid gas fuel consumption and re-refining is the best option to manage WLO with regard to abiotic depletion, eutrophication, global warming, and human toxicity environmental impacts. A further environmental option is to treat the WLO using the same mild processing technique, but then send it to expanded clay recycling to be used as a fuel in expanded clay production, as this is the best option regarding freshwater sedimental ecotoxicity, freshwater aquatic ecotoxicity, and acidification.

Conclusions It is recommended that there is a shift away from recycling and electric energy production. Although sensitivity analysis shows re-refining and energy recovery in expanded clay production are sensitive to unit location and substituted products emission factors, the LCA analysis as a whole shows that both options are good recovery options; re-refining is the preferable option because it is closer to the New Waste Framework Directive waste hierarchy principle.

Keywords Energy recovery · Life cycle assessment · Re-refining · Waste lubricant oils

1 Introduction

The Waste Lubricant Oils (WLO) Directive 75/439/EEC (Council 1975) specifies a hierarchy of waste oils management that gives preference to regeneration or re-refining, and also accepts incineration under environmentally acceptable conditions. Portugal has not yet applied the hierarchical waste management principle as it has traditionally supported energy recovery. Portugal has transposed the WLO directive into national law, as well as the amendments contained in 87/101/EEC (Council 1986) via Law Decree no. 153/2003 (MCOTA 2003). In 2006, this legal document imposed a minimum of 85 % WLO collection, 25 % re-refining, and 50 % recycling, and the creation of an integrated WLO management system through an extended producer responsibility (EPR) instrument. The entity created was SOGILUB (WLO management organization, in Portuguese *Sociedade de Gestão Integrada de Óleos Lubrificantes Usados*), which has an elaborate WLO management system, SIGOU (WLO management system, in Portuguese *Sistema Integrado de Gestão de Óleos Usados*, or SIGOU). So far, SOGILUB has achieved the national targets.

However, under the New Waste Framework Directive 2008/98/EC (European Parliament and Council 2008), WLO management should focus on the waste hierarchy. In

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addition, waste should be collected separately and, when possible, the various WLO types should not be mixed if it impedes their treatment. Incineration or co-incineration outside the national territory should be restricted to give priority to the regeneration of WLO within the Member State. Furthermore, the directive points out that Member States should take measures to encourage those options that deliver the best overall environmental outcome. Thus, specific waste streams may depart from the hierarchy if justified by possible life cycle considerations regarding the overall impact of the generation and management of such waste. In this respect, there is a need to incorporate life cycle assessments (LCAs) into waste management options, to ensure that the best environmental solution is considered.

Concerning WLO, LCA studies have focused on different technologies and recovery options. Nakaniwa and Graedel (2002) concluded that re-refined WLO used as a fuel can reduce total energy, carbon dioxide emissions, nitrogen oxides emissions, and sulfur dioxide emissions if used as a substitute for heavy fuel oil. Nakanima et al. (2001) reported that the use of non-refined WLO to produce heat and electric energy was still more favorable in terms of energy consumption and carbon dioxide, nitrogen oxides, and sulfur dioxide emissions than the use of petroleum-based thermal power plants. Kanokkantapong et al. (2009) analyzed six management scenarios for the management of WLO, where energy recovery in both cement kilns and acid clay re-refining have less environmental impact compared with solvent extraction, small boilers, vaporizing burner boilers, and atomizing burnet boilers. Boughton and Horvath (2004) showed that re-refining and distillation methods, and associated product markets should be strongly supported because they are environmentally preferable to the combustion of unprocessed used oil as fuel. Kalnes et al. (2006) tested a specific re-refining technology with combustion in cement kilns, and found it to be more environmentally favorable than combustion in a cement kiln. A European Commission study provided by Taylor Nelson Sofres (2001) pointed out that the impacts generated by regeneration plants are generally lower than those generated by incineration plants. In addition, compared with incineration in a cement kiln (where WLO replaces secondary liquid fuel, heavy fuel, coal, or petroleum coke), WLO regeneration has environmental drawbacks compared with cement kiln concerning the consumption of fossil energy resources (in three of five scenarios, the remainder were ex aequo), global climate change (in six of seven scenarios, one was ex aequo), acidification potential (in four of seven scenarios, one was ex aequo), and the emission of volatile organic compounds (VOC) (in six of eight scenarios). For human toxicity environmental impact, regeneration performed better in four of five scenarios (the other scenarios were not analyzed for such environmental impacts).

In this respect, the present paper intends to analyze the Portuguese WLO management system, SIGOU, to determine, from an environmental point of view, which improvements should be made to ensure compliance with the aims of the New Waste Framework Directive 2008/98/EC (European Parliament and Council 2008).

2 Description of WLO management in Portugal

WLO in Portugal is managed via SIGOU, the EPR management system. The treatment aims to increase the properties of WLO to enable it to be sent to various final use options, including recycling and electric energy production, re-refining, and recycling during expanded clay production. Figure 1 shows the actual SIGOU system (as at 2010).

Several waste transportation companies provide WLO collection and transport. WLO from the Madeira and Azores Autonomous Regions is also treated in continental Portugal, and is transported by ship. Collection is made along routes already defined in accordance with the capacity of the various waste producers to retain WLO and the distance to the transfer stations. However, only 80 % of all WLO produced is collected, and the remaining WLO is dispersed into the environment with negative impacts. Once collected, waste transportation companies take WLO from depositories to the treatment plants. These treatment plants are mild processing units, and use three different treatments, T1, T2, and T3. In 2010, T1 treated 19.2 % of the total WLO collected, T2 40.3 %, and T3 40.5 %.

The treated WLO is then transferred to different facilities, such as light expanded clay aggregate (LECA) producers, to be used as a fuel (energy recovery) or as an expansion agent (recycling). Treated WLO is used as an expansion agent with clays as they do not naturally expand; i.e., when

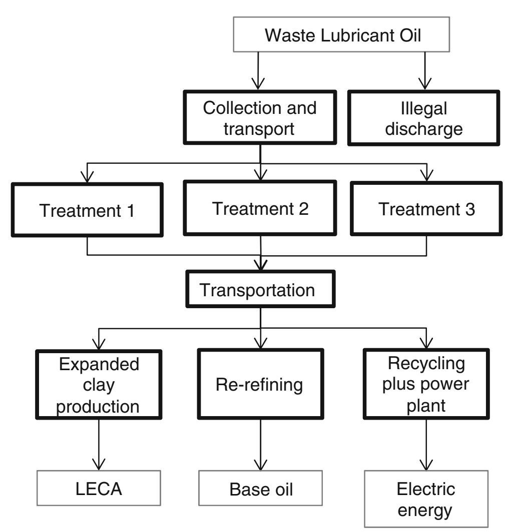


Fig. 1 Diagram of SIGOU system in 2010—actual situation

heated, clay does not significantly increase in volume. The treated WLO assists the clay to expand, making the manufacturing process easier and often safer (EIPPCB 2007). It is also transferred to thermal cracking units, where the treated WLO is converted into marine fuel oil, which is used to produce electric energy at the same unit (recycling and electric energy production). The remaining oil is then transferred to a re-refining plant in Spain. In 2010, 33.5 % of treated WLO was re-refined, 59.1 % used to produce electric energy, and 7.4 % was recycled to produce LECA.

SOGILUB has not yet measured the actual environmental impact of the SIGOU system, nor even if the SIGOU system complies with the principles of the New Waste Framework Directive 2008/98/EC (European Parliament and Council 2008). SOGILUB needs to look at the current operation of SIGOU and to initiate changes to ensure that it has the best environmental performance possible and complies with legislative obligations.

3 Methodology

To conduct a LCA of this particular WLO management system, a simplified LCA was developed and applied using the ISO 14040 family of standards (ISO 2006). Ideally, the LCA should begin at raw material extraction. However, a zero burden assumption may be applied for studying waste systems, simplifying the assessment and narrowing the LCA to the waste treatment and recovery fields. This assumption considers that the waste carries no upstream environmental burden into the waste management system (Ekvall et al. 2007); in other words, all life cycle stages prior to the product becoming waste can be omitted if they are common to all subsequent waste management options (Buttol et al. 2007).

3.1 Goals and scope definition

The aim of this study was to apply LCA to SIGOU to determine the best waste treatment and recovery options: which treatments and recovery should be retained or substituted, and should any other changes be recommended to ensure better WLO management. The actual situation described in chapter 2 will be compared with several other scenarios where treatment options are tested, as well as recovery technologies for treated WLO. Two new recovery technologies are considered, energy recovery during cement production and energy recovery during expanded clay production, and these are shown in Fig. 2, which describes the analyzed WLO system.

The LCA conducted was an attributional LCA. The functional unit applied corresponds to the annual quantity of WLO produced in 2010, 36,115.38 metric tons. This quantity also includes the amount of WLO not collected by SOGILUB (approximately 20 %).

Cut-off criteria are used to decide the processes to be included in the product system and the data gathered in the cases of (1) processes that are similar in both systems but with slight differences and (2) processes and reference flows that are specific to just one system (Humbert et al. 2009). A

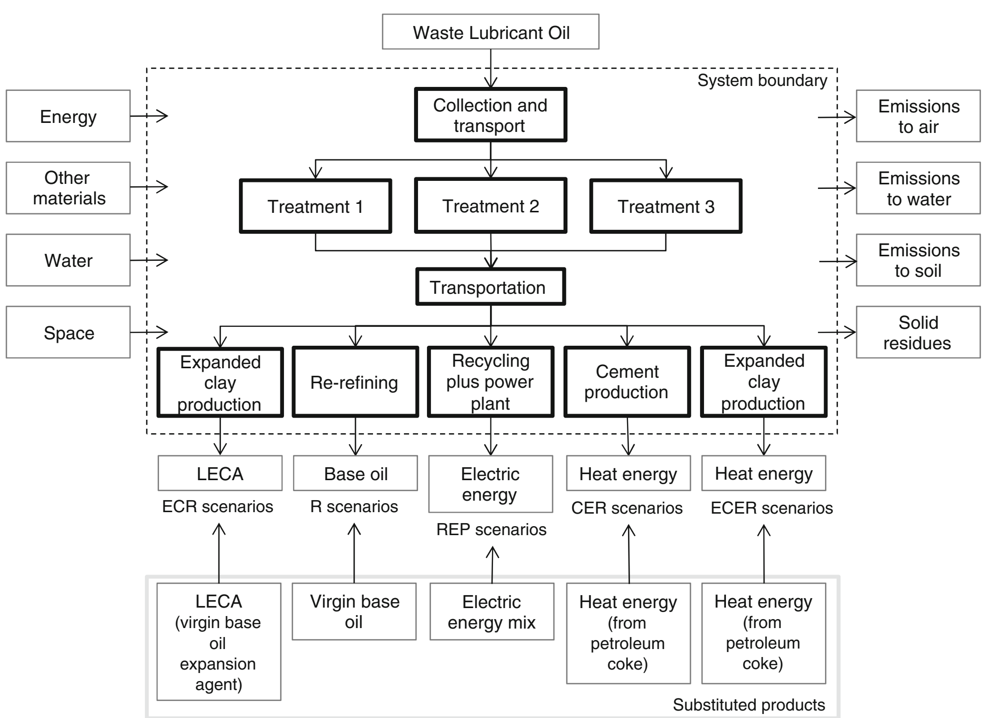


Fig. 2 Diagram of SIGOU management alternatives

cut-off level of 1 % is applied (the process is neglected if it reaches less than 1 % of the total known mass, primary energy, and impact), including that all processes with available data were taken into account, even if their contribution was less that 1 %. This cut-off rule was based on the cut-off criteria applied by Humbert et al. (2009). Therefore, the cut-off rule is used to avoid gathering unknown data, and does not neglect known data.

It should be noted that the environmental impacts from the hardware equipment (bins, buildings, and trucks) were excluded from the LCA. Nevertheless, the use of fuels, electric energy, and auxiliary materials for shipping and handling were included. Portuguese electric energy is generated using the following sources (ProBas 2010a): coal (28.10 %), fuel oil (8.37 %), natural gas (30.50 %), biomass (0.55 %), hydro (25.00 %), waste (7.00 %), geothermic (0.33 %), and wind (0.15 %).

The options analyzed in the study are based on the three WLO treatment units and the recovery technology that processes treated WLO. The treatments are identified as T1, T2, and T3. The recovery options are expanded clay recycling (ECR), where WLO is used as an expanded agent; re-refining (R), where treated WLO is regenerated to produce new lubricant oil; recycling and electric energy production (REP), where treated WLO is recycled in the facility to produce a marine fuel oil, being in the same unit used in motors to produce electric energy; cement energy recovery (CER), where treated WLO is used as a fuel; and expanded clay energy recovery (ECER), also used as a fuel in expanded clay kilns. The 15 scenarios and the actual situation include WLO collection from producers (generally automobile service stations and industries), transportation, treatment, and recovery. Note that the actual situation considers the collection of 80 % of all WLO produced and the impact of the 20 % not collected, compared with the 15 scenarios that consider all WLO produced in the reference year 2010 as collected, treated, and recovered.

The WLO system produces several co-products (materials and energy). If the material and energy flows, and the environmental load, are expressed only in relation to one function, then there is an allocation problem. To resolve the issue of allocation, the processes can be partitioned or system expansion can occur. In waste management, system expansion is appropriate in LCA because the co-products can be obtained using an alternative method to produce the "extra" product. A credit system is created, which accounts for the benefits of waste recovery. The co-products, such as electric energy, heat energy, and recycled secondary materials, are substitutes for the fuels generated using conventional technologies. The credits, in the form of negative energy and material flows, the equivalent to the quantities of the replaced primary products, are assigned to the respective processes (den Boer et al. 2005).

Co-products should have the same function as new products. The substitution ratios applied consider close loop procedures. Re-refined base oil replaces virgin base oil with a 1:1 ratio, assuming that there are no losses during the process, the quality remains equal, and there is no degradation. In the case of fuel produced to replace petroleum coke, the substitution is an open loop procedure, which only occurs the one time so there is no degradation of the material. This is also substituted at a ratio of 1:1. Electric energy is also substituted at the same ratio. The electric energy mix consumed in Portugal is composed of 15 % Spanish electric energy and 85 % electric energy produced in Portugal. Figure 2 presents the products and substituted materials for all alternatives.

3.2 Life cycle inventory

The information used in this paper was collected from SOGILUB, UMBERTO library, and information concerning air emissions was sourced from EMEP/CORINAIR. In addition, environmental licenses and environmental impact assessment studies from units operating in Portugal were used to provide information concerning the processes.

3.2.1 Waste collection and transport

WLO collection and transport are provided by several waste transportation companies, and in some instances are the same company that owns the treatment plant. WLO from the Madeira and Azores Autonomous Regions is treated in continental Portugal, with the WLO generally transported by cargo ship. The distances traveled in 2010 from the Madeira and Azores Autonomous Regions to Portugal are assumed to be 860 and 1,280 km, respectively. The distance traveled during WLO collection inside each autonomous region is unknown. In continental Portugal, collection is made along routes defined in accordance with the waste producers' capacity to retain WLO and the distance to depository areas. According to SOGILUB (2010), the total collection distance traveled in 2010 in continental Portugal was 161,273 km.

Information regarding the emissions from road collection and transportation were sourced from Knörr et al. (1997), Schmidt et al. (1998), and EMEP/EEA (2009); the diesel fuel consumption of a lorry with a 24-ton capacity is assumed to be 26 L/100 km. Information with regard to cargo ships was sourced from Borken et al. (1999), and ProBas (2005). The key emissions considered for collection and transportation were fossil carbon dioxide, dinitrogen oxide, sulfur dioxide, carbon monoxide, nitrogen oxides, and methane.

3.2.2 WLO treatment

The existing treatments used by SIGOU are mild reprocessing treatments, which remove water and sediments.

According to EIPPCB (2006), the purpose of mild reprocessing is to clean the WLO to improve its physical properties so that it can be used as a fuel by a wider variety of end users. The treatments usually involve the setting of solids and water, chemical demineralization, centrifugation, and membrane filtration. The input material is WLO, being the waste resulting from the treatment of mostly oiled sludge and wastewater.

Besides the simplicity of the treatment, each unit presents different treatment schemes, which makes each process slightly different. The respective mass balances of each treatment are presented in Table 1.

There are considerable VOC emissions during WLO treatment, and these are treated via cryogenic treatment, a biofilter, or no treatment at all. After treatment, VOC are transported and landfilled in a hazardous waste landfill. The inventory of such treatment is modeled based on EIPPCB (2003, 2006) and environmental impact assessment reports (Techninvest 2005). The hazardous waste landfill is modeled based on Weber (1990a, b), Rettenberger (1996), Förstner and Hirschmann (1997), BUWAL (1998), EMEP/CORINAIR (2007), GEMIS (2001), and Förstner and Hirschmann (1997).

Other relevant emissions are related to fuel consumption (diesel, liquid gas, fuel oil light) and output treatment. Sewage treatment is similar to all treatments, where sludge is removed and then treated in a municipal wastewater treatment plant. The wastewater treatment inventory is modeled based on ifeu (1994) and Recurso (2003). The sludge treatment concentrates the waste prior to it being sent to one of two destinations: hazardous waste landfill or cement kiln for energy recovery. The inventory applied to the sludge treatment model is based on Recurso (2003) and Lue-Hing (1998); the hazardous waste landfill is based on Weber (1990a, b), Rettenberger (1996), Förstner and Hirschmann (1997), BUWAL (1998), EMEP/CORINAIR (2007), GEMIS (2001), and Förstner and Hirschmann (1997); and with regard to cement kiln burning, the database applied was obtained from ifeu (2005) and SPINE (2003).

After the WLO has been treated, it is transported to recovery units by lorries with a 24-ton capacity, and a consumption of 26 L/100 km. The distance traveled varies between 2,500 and 26,232 km, depending on the facilities' locations (the re-refining facility is located in Spain) and the quantity of treated WLO to be transported.

3.2.3 WLO recovery technologies

The recovery technologies studied in this LCA include ECR scenarios, R scenarios, REP scenarios, CER, and ECER. The inputs and outputs involved in these recovery technologies are presented in Table 2. The emissions produced in the cement and expanded clay kilns were considered equal because both apply to rotary kilns, based on SPINE (2003), EMEP/CORINAR (2007), and EMEP/EEA (2009). With regard to expanded clay production, treated WLO may be applied as a fuel, with its recovered energetic content, or applied in the clay, which will also be consumed. It is for this reason that the products from both situations are shown in Table 2.

Concerning the R scenarios, the plant considered applies a propane deasphalting process, producing base oil, flux oil, light ends, asphaltic residue, and light fuel oil. Flux oil, light ends, and asphaltic residue are all applied as an additive to bitumen, and light fuel oil is burned in the unit to produce steam and heat.

Table 1 Products obtained from WLO system and substitution assumptions

For 1,000 kg of WLO	Input	Output	Amount	References
Treatment 1	Electric energy Diesel		11.8 MWh 14.2 kg	Recurso (2003), APA (2004)
		WLO treated	894.0 kg	
		Sludge	2.6 kg	
		Sewage	103.4 kg	
Treatment 2	Sulfuric acid Electric energy		10.0 kg 14.9 MWh	APA (2006), Techninvest (2005)
	Liquid gas		5.8 kg	
		WLO treated	897.9 kg	
		Sludge	76.0 kg	
		Sewage	36.0 kg	
Treatment 3	Electric energy Fuel oil light		15.1 MWh 4.7 kg	APA (2008), EIPPCB (2006)
		WLO treated	882.0 kg	
		Sludge	2.6 kg	
		Sewage	103.4 kg	

Table 2 Input and output quantities of the mild reprocessing methods

For 1,000 kg of treated WLO	Input	Output	Amount	References
Rotary kiln emissions (for ECR, ECER and CER scenarios)	–	Expanded clay (ECR scenarios)	10.0 kg	EIPPCB (2007), EMEP/CORINAIR (2007), EMEP/EEA (2009)
		Heat energy (for ECER and CER scenarios)	11.2 MWh	
		Carbon dioxide	3,109.5 kg	
		Sulfur dioxide	1.8E−1 kg	
		Arsenic	2.0E−8 kg	
		Cadmium	1.3E−6 kg	
		Chromium	1.6E−8 kg	
		Nickel	4.3E−6 kg	
		Nitrogen oxides	5.1 kg	
		Carbon monoxide	16.1 kg	
		NMVOC	5.0 kg	
Re-refined base oil from re-refining (R scenarios)	Sodium hydroxide		0.7 kg	ifeu (2005)
	Propane		2.2 kg	
	Hydrogen		2.0 kg	
	Steam		1.7E−1 MWh	
	Heat energy		6.7E−1 MWh	
	Electric energy		7.8E−2 MWh	
		Base oil	725.2 kg	
		Flux oil	82.2 kg	
		Light ends	14.2 kg	
		Asphaltic residue	5.18 kg	
		Sewage	79 kg	
Electric energy from WLO recycling and energy recovery (REP scenarios)	Electric energy		3.6E−2 MWh	APA (2008), EIPPCB (2006)
		Electric energy	3.2 MWh	
		Oiled water	46.7 kg	
		Heavy residues	24.8 kg	
		Carbon dioxide	19.6 kg	
		Carbon monoxide	2.0E−2 kg	
		Hydrogen fluoride	5.0E−4 kg	
		Hydrogen sulfide	2.5E−8 kg	
		Cadmium	7.2E−9 kg	
		Chromium	3.6E−9 kg	
		Nickel	2.9E−7 kg	
		Nitrogen oxides	8.0E−2 kg	
		Sulfur dioxide	0.1 kg	
		Particles	2.0E−2 kg	

Recycling and electric energy production are made through thermal cracking, where heat is used to break down long-chain hydrocarbon molecules (e.g., those found in waste oils) into shorter ones, thus generating lighter liquid fuels (EIPPCB 2006). In this way, the larger molecules of more viscous and less valuable hydrocarbons are converted into less viscous and more valuable liquid fuels (EIPPCB 2006). The outputs of the existing thermal cracking unit in Portugal include marine fuel oil, heavy residues, and oiled water. The marine fuel oil is then used in the facility to produce electric energy, released as gaseous pollutants. The oiled water and heavy residues are sent to hazardous waste landfills.

3.2.4 Auxiliary materials and substituted materials

The most relevant auxiliary materials are the fuels used during the treatment process and electric energy (the diesel

required for collection and transportation has already been mentioned). The fuels combustion emissions applied during treatment and recovery including diesel, light fuel oil, liquid gas, and marine fuel oil were inventoried based on Frischknecht et al. (1996), GEMIS database (GEMIS 2001), EMEP/CORINAIR (2007), EMEP/EEA (2009). The sulfuric acid data mentioned in treatment T2 is based on Patyk and Reinhardt (1997).

The data used to provide the system expansion (applied in this LCA to avoid allocation) required for this LCA are presented in Table 3. The inventory, conducted to produce and use substituted materials and energy, was developed using several data sources. With regard to virgin base oil production, it has been claimed that virgin base oil in Portugal contains on average 10 % synthetic base oils (Pawlak 2003; Whitby 2004), and this is taken into account in the life cycle inventory.

3.2.5 Uncollected WLO

Not all WLO is collected by SOGILUB and treated. Untreated WLO can be used in the following ways: it can be burned or be dumped in soil or water. To model the environmental impact of uncollected WLO the authors have considered that WLO is illegally discharged into waterways. The emissions from discharge were obtained from several sources, and WLO composition was sourced from EIPPCB (2006), ifeu (2005), and ERM (2008). The inventory of this process is comprised of almost 40 substances. Table 4 presents a list of the main substances.

3.3 Life cycle impact assessment

UMBERTO 5.5 (ifeu 2009) software was used to develop the LCA in this paper. Environmental indicators from Guinée et al. (2002) were used to represent the various impact categories: abiotic depletion (AD), acidification (Acid), eutrophication (Eut), global warming (GW), human toxicity (HT), freshwater aquatic ecotoxicity (FAE), freshwater sedimental ecotoxicity (FSE), and photochemical oxidation (PO). Table 5 shows the environmental impact of each SIGOU operation unit.

Table 4 Summary of main substances released from uncollected WLO

Substances	Emissions from 1,000 kg of uncollected WLO (g)
Ethylene	950,000
Aromatic organic compounds	220,000
o-Xylene	2,005
Calcium	1,975
Chlorine	1,200
Zinc	1,055
Toluene	1,011

4 Discussion of impact assessment

4.1 WLO management scenarios

In this section, the results of the assessment are presented and the scenarios are compared, presented in Fig. 3 and Table 5. The more negative the scenario, the better the environmental performance; these scenarios avoid the various environmental impacts (due to the system expansion, where co-products replace virgin materials). No particular WLO management alternative is shown to be the better performer from an environmental point of view. For the environmental impact categories AD, Eut, GW, and HT, the T2R scenario performed the best, causing less environmental damage. Concerning the impact categories Acid, FAE, and FSE, T2ECER emerged as the best option, with a healthier environmental profile (more negative).

The results obtained for T2R are related to the avoidance of natural resource consumption, because re-refining lessens the need for the production of virgin base oils. Virgin base

Table 3 Summary of life cycle inventory data sources for expanded systems and avoided products

Product obtained	Substitutes assumed	Substitution ratio assumed	Source of data of substitutes
Re-refined base oil from re-refining	Virgin base oil	1:1	ifeu (2005)
LECA, where WLO is used as expansion agent	Virgin base oil	1:1	ifeu (2005)
Electric energy from WLO recycling and energy recovery	Electric energy mix consumed in Portugal	1:1	GEMIS (2001), ProBas (2010a,b)
Heat from WLO used as fuel in cement kiln and in LECA production	Petroleum coke	1:1 (based on energy content)	NREL (2003), ProBas (2005), Borken et al. (1999), GEMIS (2001), EMEP/CORINAIR (2007), ProBas (2000)

Table 5 Contribution of each WLO solution on environmental impact category

WLO scenarios	AD (kg Sb eq)	Acid (kg SO_2 eq)	Eut (kg PO_4^{3-} eq)	GW (kg CO_2 eq)	HT (kg DCB eq)	FAE (kg DCB eq)	FSE (kg DCB eq)	PO (kg C_2H_4 eq)
Actual	−4.85E+05	8.39E+04	5.04E+04	−4.20E+06	1.12E+06	1.64E+08	5.10E+08	4.74E+03
T1ECR	−7.65E+05	−9.65E+04	6.87E+03	2.24E+07	−1.53E+03	1.03E+03	2.40E+03	1.33E+03
T1R	−1.12E+06	−2.07E+05	−6.27E+03	−3.95E+07	−1.54E+05	1.27E+03	2.91E+03	−8.52E+03
T1REP	−2.33E+05	3.28E+05	7.65E+04	1.24E+07	4.60E+05	7.17E+02	2.31E+03	4.80E+03
T1CER	−8.65E+05	−7.10E+05	−4.47E+03	−3.31E+07	−6.32E+04	1.29E+02	2.18E+03	−2.98E+04
T1ECER	−8.67E+05	−7.12E+05	−4.94E+03	−3.34E+07	−8.97E+04	−2.16E+02	1.67E+03	−2.98E+04
T2ECR	−7.75E+05	−1.17E+05	4.76E+03	2.17E+07	−7.81E+04	2.45E+02	3.50E+02	1.62E+04
T2R	−1.13E+06	−2.29E+05	−8.64E+03	−4.06E+07	−2.42E+05	3.41E+02	6.49E+02	6.28E+03
T2REP	−2.42E+05	3.09E+05	7.46E+04	1.15E+07	3.78E+05	−1.64E+02	1.25E+02	1.97E+04
T2CER	−8.77E+05	−7.33E+05	−6.79E+03	−3.41E+07	−1.49E+05	−7.72E+02	−3.52E+01	−1.51E+04
T2ECER	−8.78E+05	−7.35E+05	−7.10E+03	−3.44E+07	−1.67E+05	−1.00E+03	−3.80E+02	−1.51E+04
T3ECR	−7.60E+05	−1.13E+05	6.07E+03	2.31E+07	−4.43E+04	6.91E+02	1.30E+03	9.35E+02
T3R	−1.11E+06	−2.25E+05	−7.35E+03	−3.83E+07	−2.20E+05	5.91E+02	1.30E+03	−8.83E+03
T3REP	−2.36E+05	3.05E+05	7.46E+04	1.31E+07	4.03E+05	2.80E+02	1.06E+03	4.35E+03
T3CER	−8.62E+05	−7.20E+05	−5.56E+03	−3.19E+07	−1.30E+05	−5.23E+02	6.00E+02	−2.98E+04
T3ECER	−8.62E+05	−7.21E+05	−5.60E+03	−3.20E+07	−1.33E+05	−5.54E+02	5.55E+02	−2.98E+04

oil production is a process that emits pollutants such as greenhouse gases (responsible for GW impact), nitrogen oxides, benzene (which affects HT levels), and it causes eutrophication.

In the case of T2ECER, the substitution of petroleum coke by the treated WLO is beneficial to the environment, as it avoids the emission of sulfur dioxide and nitrogen oxides (pollutants responsible for Acid), methylene oxide (responsible for effects on FAE and FSE), and nickel (affects FSE).

It is not only because of the recovery option that these two scenarios have presented the best results; the T2 treatment is also the best treatment when compared with the other WLO treatment options (see Fig. 3). The main influencing factors regarding these results are the type of fuel used in the unit to treat WLO and the quantity of fuel required. As well as using electric energy, treatments T1 and T3 use diesel and fuel oil light, which release more pollutants (sulfur dioxide, nitrogen oxides, carbon dioxide, dinitrogen oxide, methane, benzene, nickel, methylene oxide) during its production and combustion compared with liquid gas used in T2. T2 only fell below the other WLO treatments with regard to photochemical oxidation because of VOC emissions (specifically styrene and toluene) from the biofilter. The WLO treatment and recovery options are the most relevant WLO management stages from an environmental point of view.

The actual present day WLO scenario is the worst management option regarding HT, FAE, and FSE because of the illegal discharge of WLO. The main uncontrolled pollutants released are benzo(*a*)pyrene, naphthalene, polycyclic aromatic hydrocarbons, ethylene, and vanadium. Such a result reinforces the need for SOGILUB to better manage WLO and to ensure the collection of all WLO.

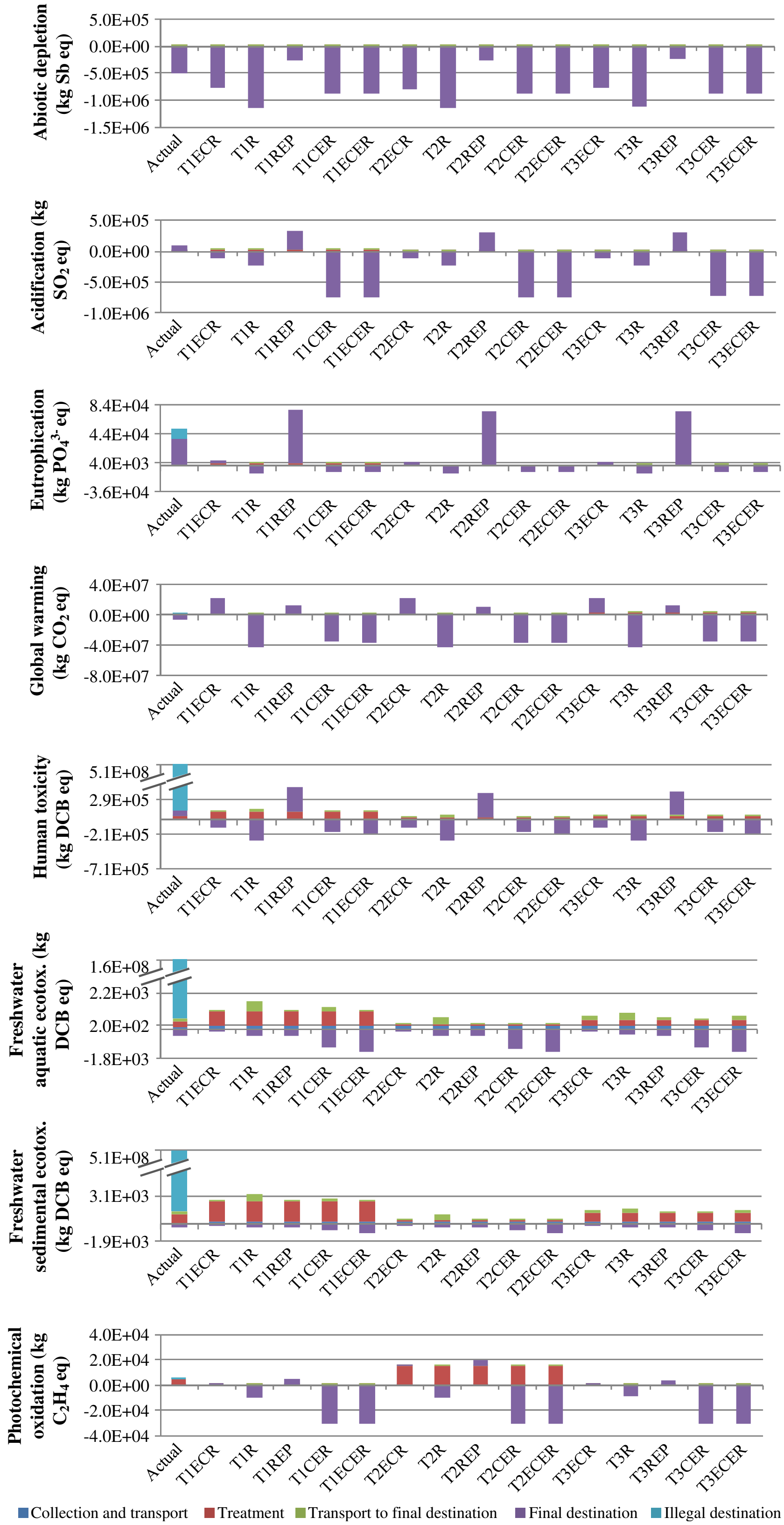
The second worst scenario is T1REP concerning AD, Acid, and Eut. The recycling of WLO into electric energy is not desirable because of the nitrogen oxides and sulfur dioxide emissions during marine fuel oil combustion. Furthermore, the cleaner electric energy production in Portugal does not compensate for the acidification and eutrophication pollutant emissions from T1REP.

4.2 Sensitivity analysis

A sensitivity analysis was conducted to observe the influence of a change in the inventory data on the impact assessment results. The first sensitivity analysis was based on an increase of recycling efficiency of treated WLO prior to electric energy production. This change is reflected in REP scenarios and the present day scenario. The authors assumed that efficiency increased to 65.5 %. The analysis confirmed that efficiency in the recycling scenario did not influence the results.

A further sensitivity test was carried out on the distance to the re-refining plant. The location of the re-refining plant was assumed to be in Germany, with transportation by cargo ship (data sourced from Borken et al. 1999). This location was justified by the absence of re-refining industries in Portugal, which in turn justified the transportation of WLO to other countries (Germany is assumed to be a possibility by both the authors and SOGILUB). The results are sensitive for Eut and HT impacts, and T2CER was the best scenario for HT and T2ECER for Eut. The T2ECER

Fig. 3 Contribution of each WLO solution on environmental impact category by life cycle step



scenario was also the best at managing WLO regarding Acid, FAE, and FSE environmental impact categories.

The last factor tested was the emissions from petroleum coke combustion. Here, the intention was to observe if an

increase in the emission factors of a substitute product could cause an increase in the avoided system of such a magnitude as to change the results; e.g., scenarios where petroleum coke is substituted would be better than the re-refining scenarios (like T2R). The petroleum coke combustion emissions considered in the LCA are the median values from the sources used. In this case, an increase of 10 % for each pollutant (carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, cadmium, arsenic, chromium, nickel, non-methane VOC, and dinitrogen oxide) and particles (PM_{10}) was tested. The results from the LCA are sensitive to this factor, with regard to the impact of GW, where the results showed that T2CER and T2ECER were more suited to manage WLO than T2R.

5 Conclusions

The present LCA study was intended to compare different WLO management alternatives in Portugal. Using the actual present day situation and 15 management scenarios, it was found that none of the scenarios had the highest or lowest environmental profile for all environmental impact categories. Based on these comparisons, the management alternative that best performed in the most environmental impact categories was T2R, i.e., where WLO is treated with treatment T2 and then sent for re-refining. T2ECER, a scenario where energy recovery occurs in expanded clay production units, also presented reduced impacts in several environmental impact categories.

Such results clearly recommend to SOGILUB that it should implement treatment T2 as the main method to treat WLO, and that recovery options should include re-refining and/or energy recovery in expanded clay production units. Re-refining is the preferable option as it is more in line with the waste hierarchy principle defined in the New Waste Framework Directive 2008/98/EC (European Parliament and Council 2008). SOGILUB should also promote the collection of *all* WLO in Portugal because the environmental impact of uncollected WLO is significant and that practice must stop immediately. The results obtained from T1REP, T2REP, and T3REP suggest that the recycling and electric energy production of treated WLO should no longer be a WLO management option.

Concerning the sensitivity analysis, it was observed that the distance of the re-refining plant and the increase in emissions factors from petroleum coke combustion are sensitivity factors that will change LCA results. If decisions relate to the location of infrastructures or diminutive differences in the same technologies (e.g., an expanded clay unit that does not use petroleum coke as a fuel but instead another fuel), then the LCA results may not be maintained.

In relation to the future development of this LCA, one aspect that should be studied to improve the SIGOU system is an increase in the quality of WLO collected (possibly using a source-separated collection system for several types of WLO). If higher quality WLO was collected, then mild processing treatments (T1, T2, and T3) could be avoided and the WLO could be sent directly to its recovery.

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